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REPORT MI-145

Field Trip Guide to Alkali-Carbonate Reactions in Kingston, Ontario

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FIELD TRIP GUIDE TO ALKALI-CARBONATE REACTIONS IN KINGSTON, ONTARIO

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Abstract:

The alkali-carbonate rock reaction was first recognized in the Kingston area and was first described by Swenson in 1957 following deterioration of concrete containing aggregate from the Pittsburg quarry. The reaction occurs in Portland cement concrete between the cement alkalies (sodium and potassium hydroxide) and the aggregates (quarried dolomitic limestones and calcitic dolostones with medium to high clay contents) and causes expansion and cracking. The Gull River Formation, 60 metres thick, is the source of the aggregate responsible for the reactivity.

At Stop 1 of the itinerary (Ministry of Transportation laboratory), four experimental sidewalk sections built in 1985 with reactive aggregate from the Pittsburg quarry (Stop 4) and a variety of cements have expanded approximately double the amount measured in the conventional Canadian Standards Association procedure. Reactive aggregate has also been produced from the Frontenac quarry (Stop 2). The Polson Park subdivision (Stop 3) was built in 1957 with reactive aggregate from the Pittsburg quarry and an extra low alkali cement; many sections of curb and gutter show mild pattern cracking but the performance is satisfactory.

Résumé:

La réaction alcali-carbonate a été reconnue en premier lieu dans la région de Kingston et a été initialement décrite par Swenson en 1957 suite à la détérioration du béton renfermant des granulats de la carrière Pittsburg. Dans le béton fait avec le ciment Portland, cette réaction se produit entre des alcalis du ciment (hydroxydes de sodium et potasse) et des granulats (calcaires dolomitiques et dolomies calciques, extraits des carrières, avec des contenus d'argile variant de moyen à élevé) et, par conséquent, est la cause d'expansion et fissures. Le granulat responsable de la dite réaction provient de la formation de Gull River, ayant une épaisseur de 60 m.

A l'arrêt No. 1 de l'itinéraire (laboratoire du ministère des Transports), quatre sections expérimentales de trottoir construites en 1985 avec granulat réactif de la carrière Pittsburg (Arrêt No. 4) et une variété de ciments ont subi l'expansion d'environ deux fois la dimension mesuré dans la procédure de l'Association Canadienne de Normalisation. Du granulat réactif a été produit aussi de la carrière Frontenac (Arrêt No. 2). La subdivision de Polson Park (Arrêt No. 3) a été construite en 1957 avec du granulat reactif de la carrière Pittsburg et un ciment extrêmement bas en alcalis; plusieurs sections de bordure de trottoir et de caniveau montrent une fissuration polygonale douce mais la performance est satisfaisante.

Keywords: aggregates, performance, petrographic examination, concrete, alkalies, Portland cement, testing, alkali-aggregate reaction, expansion, cracking

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FIELD TRIP GUIDE TO ALKALI-CARBONATE REACTIONS IN KINGSTON, ONTARIO

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Field trip guidebook prepared for the meeting of the Canadian Standards Association subcommittee on cement-aggregate reactivity (CSA-A5) held in Kingston, Ontario, October 11-12, 1990

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THIS REPORT IS PUBLISHED WITHOUT PREJUDICE AS TO THE APPLICATION OF THE FINDINGS

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PART 1 - INTRODUCTION

ALKALI-CARBONATE REACTIVITY

The alkali-carbonate rock reaction was first recognized in the Kingston area and was first described by Swenson in 1957. The reaction occurs with quarried dolomitic limestones and calcitic dolostones with moderate to high clay contents and can cause excessive expansion and cracking of Portland cement concrete within three years. The expansion of the concrete is caused by swelling of individual coarse aggregate particles. The swelling is probably due to adsorption of water on previously dry clay surfaces, exposed as a result of microcracking caused by dedolomitization of euhedral dolomite crystals reacting with alkalies from the cement (Gillott, 1964).

There are four procedures for testing aggregate for the alkali-carbonate reaction:

1. Petrographic examination of thin sections of the rock, to observe the characteristic reactive texture of euhedral dolomite rhombs in a clayey, micritic matrix (Gillott, 1963).

2. The rock-cylinder expansion test (ASTM C586) to measure expansion in alkali solutions.

3. A quick chemical test to identify those aggregates that have a bulk composition corresponding to known reactive aggregates (Rogers, 1986).

4. The concrete prism expansion test (CSA A23.2-14A), normally used as the specification method to measure expansion of concrete containing aggregate indicated by the other tests to be potentially reactive.

GEOLOGY OF THE KINGSTON AREA

Deformed Precambrian metamorphic and igneous rocks and overlying gently dipping Paleozoic sedimentary rocks are extensively exposed in the Kingston area (Figures 1, 2, 3, and 4). A geological compilation map of the area was prepared by Kingston, Papertzian and Williams (1985) and the Paleozoic geology was revised by LeBaron and

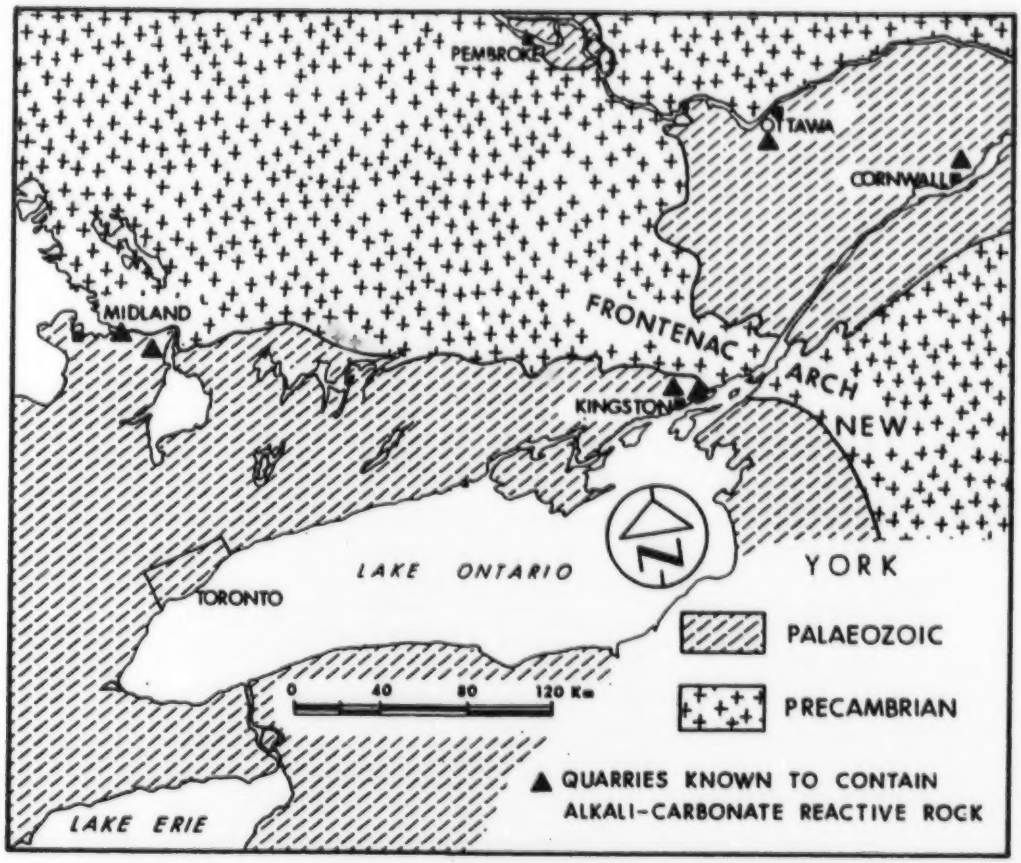

Figure 1. Index map of Kingston and adjacent areas.

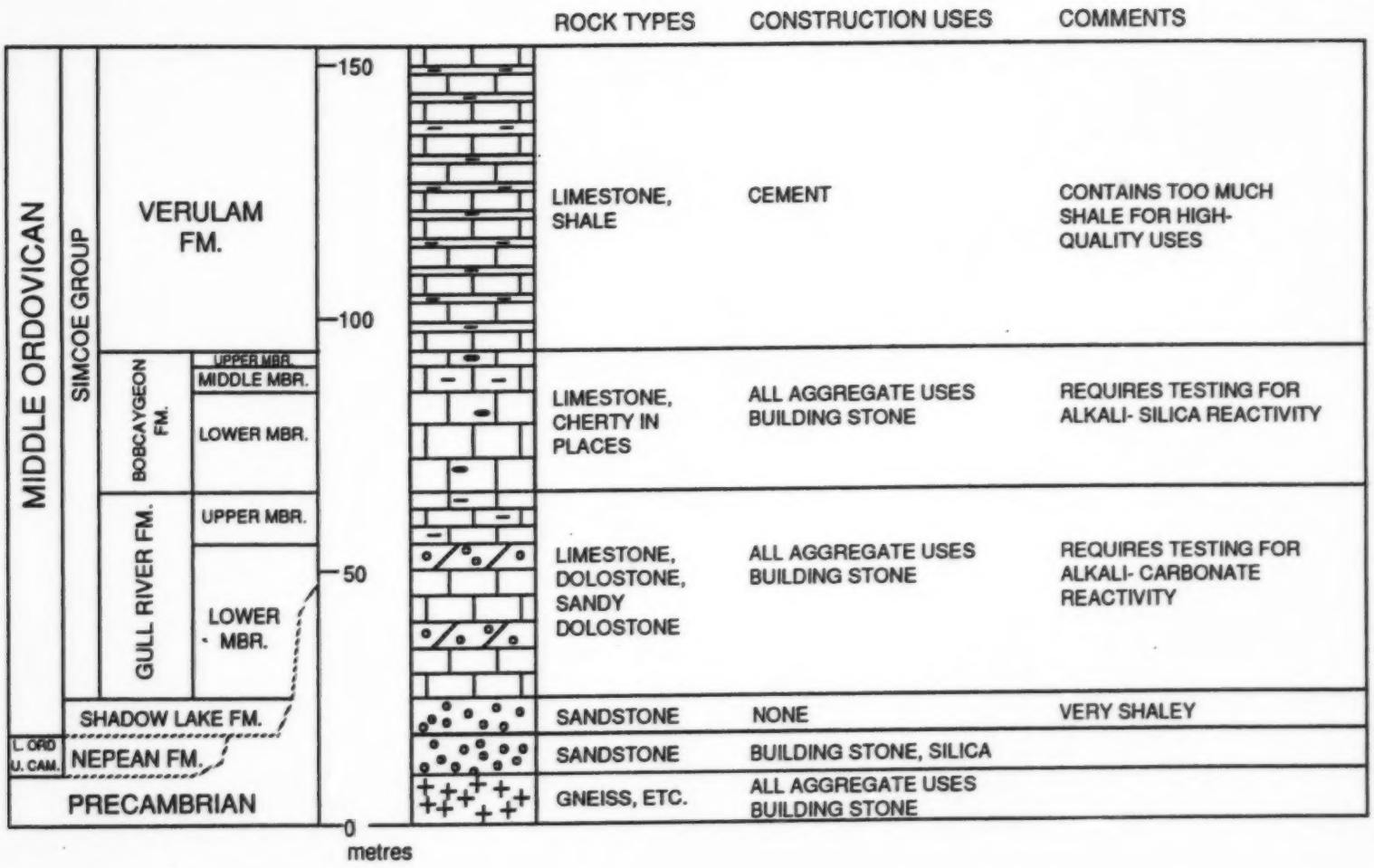

Figure 2. Generalized stratigraphy of the Kingston area.

PALEOZOIC

MIDDLE ORDOVICIAN

6 Verulam Formation

5 Bobcaygeon Formation

4 Gull River Formation

3 Shadow Lake Formation

UPPER CAMBRIAN-LOWER ORDOVICIAN

2 Nepean Formation

PRECAMBRIAN

1 Undifferentiated metamorphic and igneous rocks

Geological contact

Fault (arrow indicates down-dropped block) and approximate displacement (in metres)

30

A B Geological section (see Figure 4)

Figure 3. Geological map of the Kingston area (from LeBaron and Williams 1989).

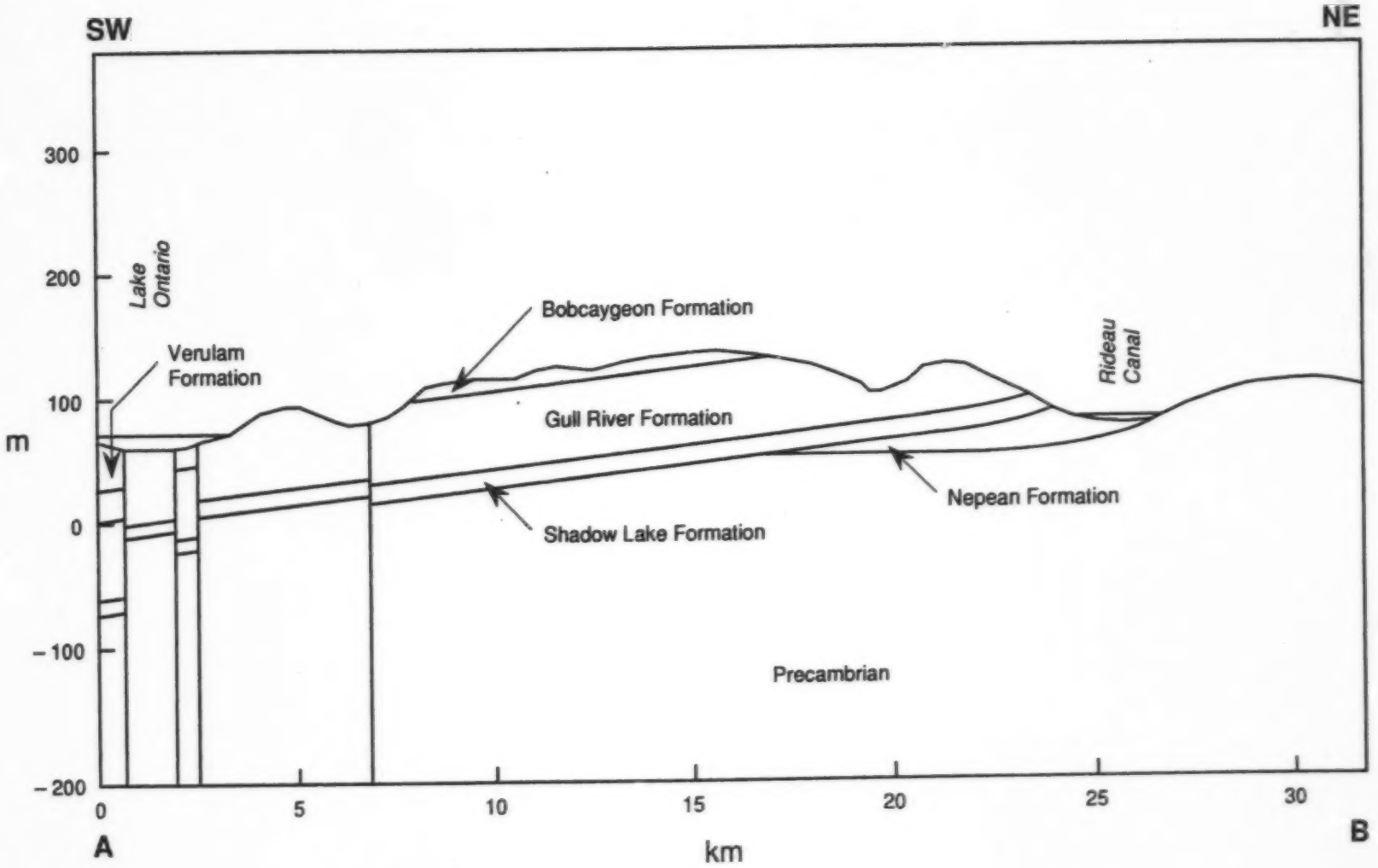

Figure 4: Geological section of the Kingston area.

Williams (1990). The physiography has been described by Chapman and Putnam (1984). Areas in which Precambrian bedrock is exposed comprise part of the Leeds knobs and flats physiographic region and areas in which Paleozoic bedrock is exposed comprise part of the Napanee limestone plain.

The Precambrian basement consists of metasedimentary and metavolcanic rocks (including gneiss, amphibolite, quartzite and marble) which have been intruded by felsic to mafic plutons. The principal outcrop area of basement rock, located northeast of Kingston, occurs along a southeasterly-trending uplift (the Frontenac Arch) which separates the Lake Ontario Lowland and the Ottawa Valley. Local exposures of Precambrian rock southwest of the uplift either represent erosional remnants or occur at the bottom of river valleys.

The sedimentary rocks of the Lake Ontario Lowland in the Kingston area are of Upper Cambrian to Lower Ordovician (Nepean Formation) and Middle Ordovician (Shadow Lake, Gull River, Bobcaygeon and Verulam Formations, in ascending order) age. The Nepean Formation consists of fine to coarse grained quartz sandstone, partially calcareous in the upper part. It is up to approximately 30 metres thick to the northeast of Kingston but does not exist elsewhere in the area. The Shadow Lake Formation consists of interbedded red and green conglomerate, sandstone and mudstone. It is up to 10 metres thick but does not exist in the vicinity of prominent Precambrian erosional remnants. The Gull River Formation has two members and consists of thin to medium bedded microcrystalline to fine crystalline limestone, with interbeds of dolostone and sandy dolostone in the lower member. It is approximately 60 metres thick and is the source of the aggregate responsible for alkali-carbonate reactivity in the Kingston area. The Bobcaygeon Formation has three members and consists of thin to massive bedded microcrystalline to coarse crystalline limestone, with interbeds of shale in the middle member. It is approximately 25 metres thick. The Verulam Formation consists of interbedded thin to medium bedded microcrystalline to coarse crystalline limestone and shale and is approximately 55 metres thick.

The Paleozoic rocks dip southward at approximately 4 metres per kilometre and are cut by steeply dipping joints which form five sets (north-northeast, northeast, east-northeast, east-southeast and southeast). The bedrock is transected by steeply dipping normal faults of the east-northeasterly-trending Southern Great Lakes rift zone. Prominent topographic depressions (the Bay of Quinte and the St. Lawrence River) follow fault traces. Vertical fault displacement is up to 75 metres in the Kingston area.

PART 2 - ITINERARY

STOP 1 (MINISTRY OF TRANSPORTATION LABORATORY)

The Ontario Ministry of Transportation (Eastern Region) laboratory is located at the northeast corner of Counter Street and Sir John A. MacDonald Boulevard (Figure 5). Meet at the rear of the complex by the Regional Laboratory building.

At the time we experienced the alkali-carbonate reaction (ACR) in Cornwall (Rogers, 1986), it was noted that the field expansion seemed to be significantly greater than that measured in the laboratory using concrete prisms. To investigate this we built some sidewalks in 1985 and compared field expansion with laboratory expansion.

CONSTRUCTION AND TESTING

Four sidewalk sections were constructed using reactive aggregate from the Pittsburg quarry (see below) and a variety of cements. Each section was about 3.7 m by 1.2 m, divided into three 1.2 m squares. The details of the concrete mixtures are given in Table 1. The concrete was mixed on site by weigh batching using a 0.17 m^3 mixer. Stainless steel studs were set in the concrete and measured with a 51 cm span Whitemore strain gauge. The concrete slabs were cured with wet burlap for 4 days. An asphalt concrete apron was placed around each section several weeks after the concrete had been placed.

Nine 75 by 100 by 405 mm concrete prisms were made from nearly every mixture. These prisms were demoulded in the laboratory and measured following CSA A23.2-14A. The prisms were stored in a variety of conditions:

Conventional moist room curing at 23°C;
Immersion in a 5% sodium chloride solution at 23°C; and
Over water in a sealed box with filter paper wicks at 38°C.

The sidewalks have been exposed to five winters. During the winter there are frequent cycles of freezing and thawing with periodic dispersal of sodium chloride crystals on the surface as would normally occur on sidewalks in this area. Results of expansion measurement of the sidewalks and prisms are shown in Figures 6 to 11.

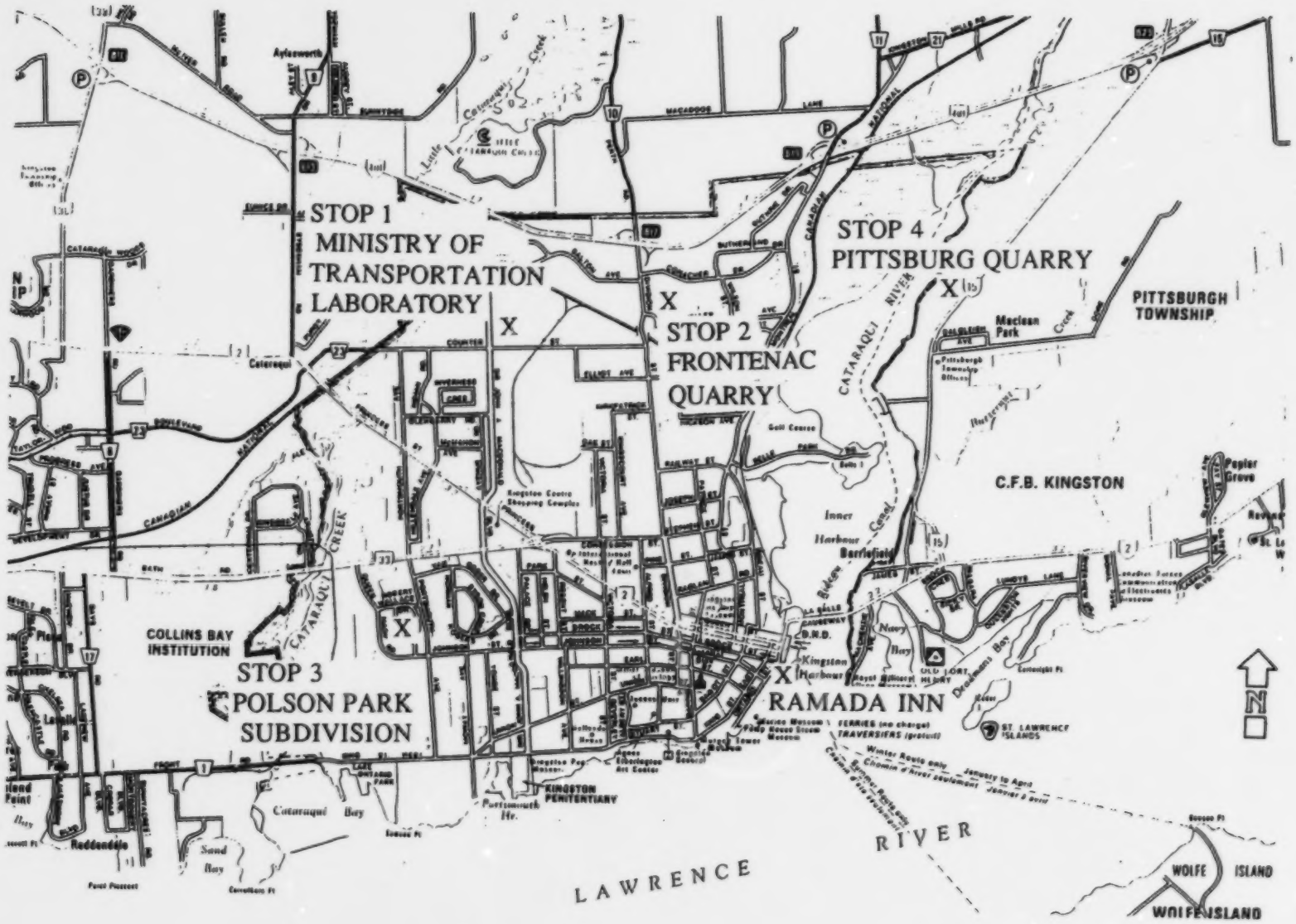

Figure 5. Field trip itinerary.

Table 1 Summary of mixture design and field test data for Kingston Sidewalk sections.

MIXTURE AND TEST SECTION NO.	1	2	3A	3B	4
Air content when plastic	4.5	6.0	-	5.5	9.0
A23.2-4C	7.5	5.5			6.2
Slump in mm	50	70	-	70	70
A23.2-5C	85	70			90
Effective w/c ratio	0.57	0.52	0.51	0.54	0.53
Compressive Strength 7 day	27.1		18.3	-	23.6
A23.2-9C	26.6		18.1	-	21.0
Compressive Strength 28 day	31.6	40.9	31.4	37.0	25.6
A23.2-9C	32.3	38.7	29.2	37.0	26.2
Concrete Proportions					
coarse aggregate (kg)	1105	1115	1110	1110	1120
fine aggregate (kg)	730	730	730	730	740
cement (kg)	310	310	310	310	310
total water (kg)	192	175.8	180.6	180.6	177.4
Cement Properties			Slag 25%	Slag 50%	
% Na_2O	0.62	0.34	0.32	0.32	0.62
% K_2O	0.63	0.34	0.53	0.53	0.63
% equivalent Na_2O	1.04	0.56	0.67	0.67	1.04
Alkali content of the mix as % equivalent Na_2O by mass of cement	1.04	0.56	0.95	0.86	1.25
Alkali content of the mix expressed as kg/m^3 Na_2O equiv.	3.22	1.74	2.95	2.65	3.88

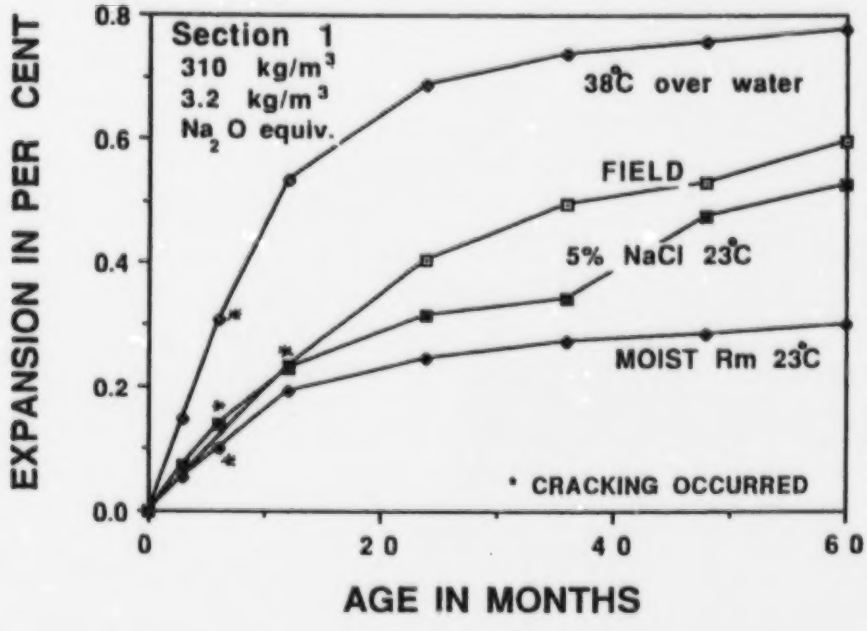

Figure 6. Expansion of sidewalk 1 and prisms.

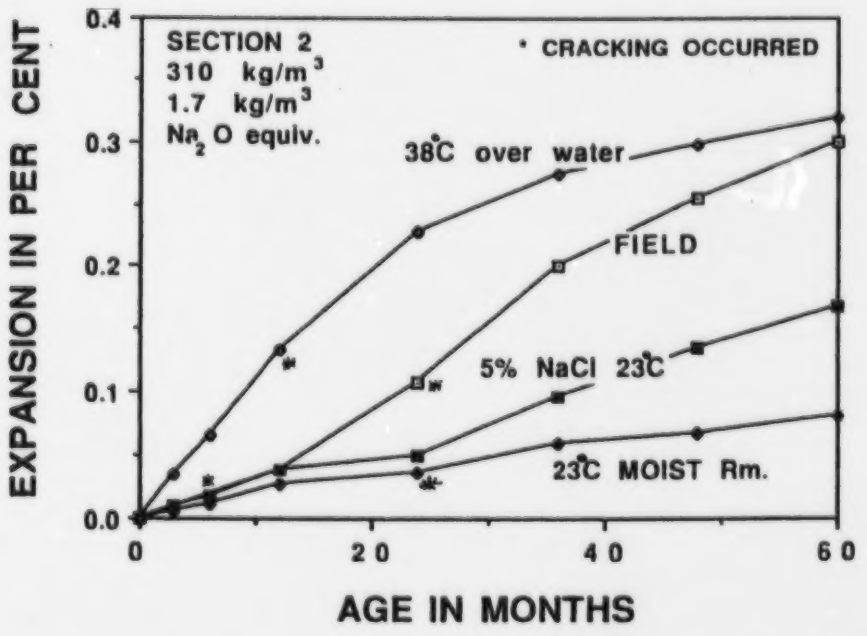

Figure 7. Expansion of sidewalk 2 and prisms.

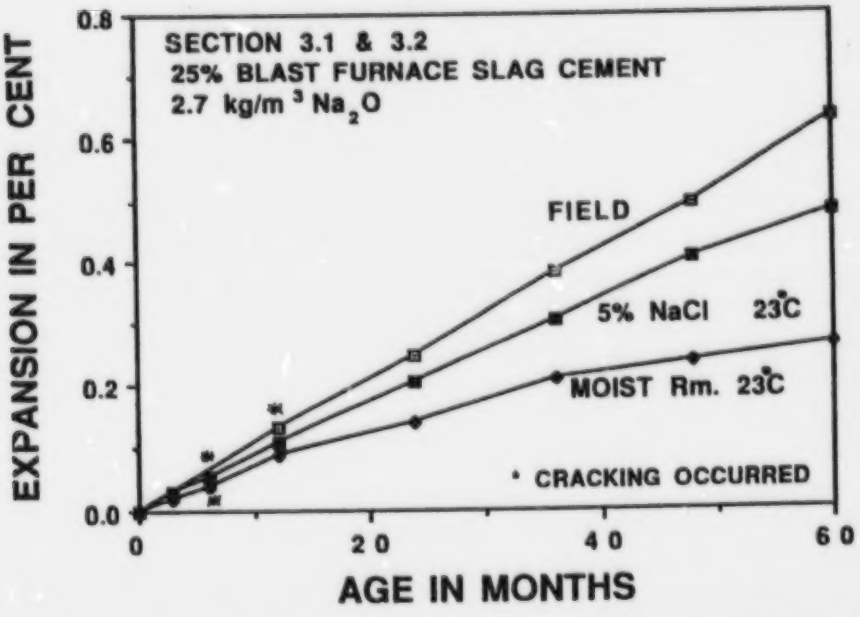

Figure 8. Expansion of sidewalk 3.1-3.2 and prisms.

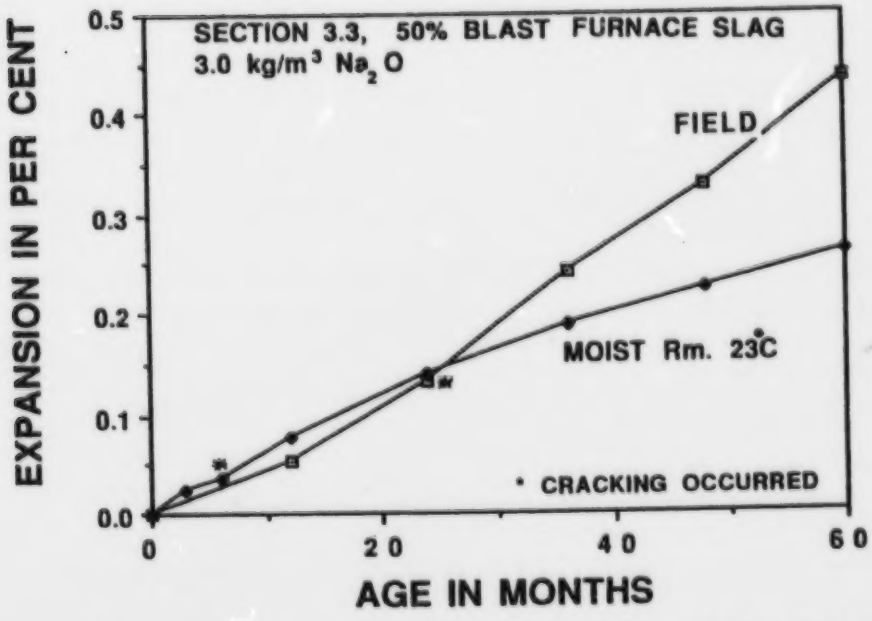

Figure 9. Expansion of sidewalk 3.3 and prisms.

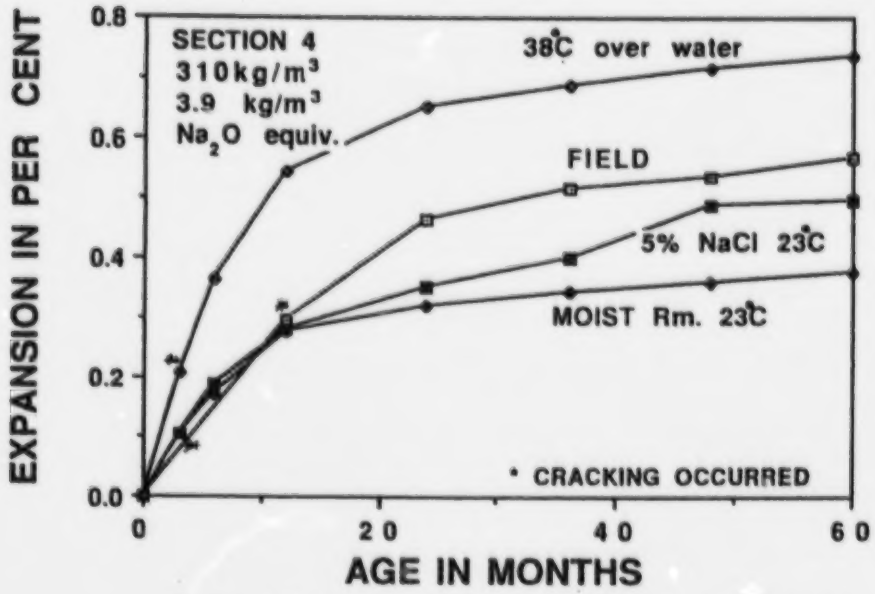

Figure 10. Expansion of sidewalk 4 and prisms.

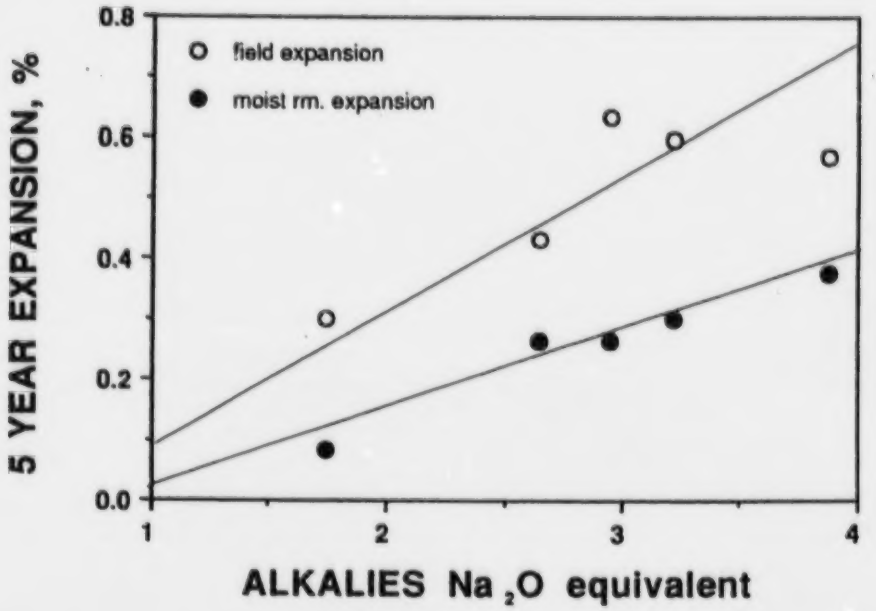

Figure 11. 5-year expansion of sidewalks and prisms.

CONCLUSIONS

Expansion of concrete in the conventional CSA procedure was about half of that measured in the field after five years (Figures 6-10). At an age of one year, expansion was about the same, but after that, field expansion was considerably greater. It is suspected that this is because of alkali leaching from the prisms in the moist room (Rogers and Hooton, 1989). Leaching of alkalies from the concrete reduces the amount of alkali available to participate in alkali-aggregate reactions. Alkali leaching is a much slower process in the field because of longer transportation paths and the fact that concrete is not continually exposed to precipitation. Also, the temperature of the sidewalks in the summer is often over 30°C which probably helps to speed the reaction process in contrast to the constant 23°C in the curing room.

Storing the concrete in either 5% sodium chloride or at 38°C resulted in considerable increases in expansion. Storage in sodium chloride slightly underestimated field expansion and 38°C storage resulted in rather more than field expansion. Expansion was roughly proportional to the alkali content of the concrete (Figure 11).

The section constructed with blast furnace slag (bfs) cement showed an unusual rate of expansion. Both the concrete made with 25% bfs and 50% bfs showed an almost constant rate of expansion over the five year period. This is in marked contrast to the sections with normal Portland cement which show a reduced rate of expansion after a period of about one year in the laboratory and two years in the field. This may have been due to the reduced permeability of the bfs concrete which resulted in less expansion at early ages, but did not affect expansion in the long term.

If you want to estimate field expansion of ACR concrete, do not assume that the moist curing room is the place to do it. It would be interesting to know to what extent these observations apply to the alkali-silica reaction. Further work will involve measuring strength, alkali and chloride profiles and continued expansion to about 10 years or longer. An investigation of the field and laboratory concrete for the presence of dedolomitization products, such as brucite, would make an interesting M. Sc. project for a mineralogist.

STOP 2 (FRONTENAC QUARRY)

The Frontenac quarry (Hewitt, 1960, p. 67-69) is located immediately east of Division Street and 500 metres south of Highway 401 (Figure 5). It was in operation from the early part of the century until the 1960's, producing crushed stone for road construction and is currently being developed for other uses. Twenty-five metres of the Lower Gull River Formation are exposed; the section consists mainly of limestone (commonly dolomitic), with dolostone interbeds from 13 to 18 metres above the base.

A notable feature of the quarry is the exposure of a fault of five metres vertical displacement (northeast side down). Brecciation and calcite-pyrite veining have occurred within the fault zone which dips 65 degrees to the northeast.

Concrete prism expansion tests have been conducted on Frontenac quarry aggregate (Smith, 1964, p. 129). Expansions at 84 days were as follows: 0.019% (1958 production); 0.058% (upper 3.65 metres); and 0.034% (lower 10.95 metres).

STOP 3 (POLSON PARK SUBDIVISION)

The Polson Park subdivision was built in 1957 at the northwest corner of Portsmouth and Johnson Avenues (Figure 5). Ed Swenson had shown in his work that a so called 'low alkali' cement as defined by ASTM (<0.6% Na_2O equiv.) was not low enough to prevent cracking of concrete prisms in the laboratory. Canada Cement made an extra special low alkali cement at their Woodstock plant. Normally the cement there is about 0.45% Na_2O. Although we could not find the records, we believe that the cement used in the subdivision sidewalks and curb and gutter had an alkali content of 0.31% Na_2O equiv. (0.14% Na_2O and 0.26% K_2O). There is extensive discussion of the laboratory use of this cement in Swenson and Gillott (1960). They suggested that for Kingston rock (Pittsburg upper lift) a maximum alkali content of 0.45 or 0.40% should be used.

The sidewalks were built using coarse aggregate from the upper seven metres (upper lift) of the Pittsburg quarry with an igneous and metamorphic rock type fine aggregate from Sweet's Sand and Gravel (now owned by Tackaberry) located at the junction of Highways 15 and 32. The sidewalks were placed by McGinnis and O'Connor Limited who owned the quarry. Swenson and Gillott (1964) reported that the sidewalks had been

in place for 6 years and there was no "...visible sign of distress due to excessive expansion or cracking". It seems that after these sidewalks were constructed, the Ontario cement producers declined to make a sufficiently low alkali cement to allow these expansive rocks to be used in concrete. For many years concrete aggregates have been imported into the Kingston area or produced by selective quarrying of the Ordovician bedrock.

In 1990 many sections of curb and gutter showed extensive mild pattern cracking (Plate 1). The cracks had been mainly filled with secondary deposits of calcium carbonate, with a light coloured staining around the cracks. There were signs of mild expansion causing closing of construction joints. The concrete was mainly intact and judged to be performing satisfactorily after 33 years. The sidewalks did not show pattern cracking, possibly because they were less exposed to de-icing salt than the curb and gutter. The cement mortar was largely scaled off the aggregate particles. There were several (<10) coarse aggregate popouts per square metre.

STOP 4 (PITTSBURG QUARRY)

The Pittsburg quarry (Hewitt, 1960, pp. 69-71; Dolar-Mantuani, 1975, pp. 8-15; Derry et al., 1989, pp. 140-143) is located between Highway 15 and the Cataraqui River, 3 kilometres south of Highway 401 (Figure 5). It has been in operation since 1949 and is currently owned by Frontenac Aggregates and Construction.

20.6 metres of the Lower Gull River Formation are exposed in the quarry (Figure 12). The section consists mainly of limestone, commonly dolomitic. The upper 4.4 metres of the first lift contain dolostone interbeds (equivalent to those of the Frontenac quarry). The upper 1.3 metres of the second lift consist of sandy dolostone (the green marker bed of Hewitt, 1960) and the lower 1.7 metres of dolostone. Interbeds of dolostone are common in the third lift. The upper 2.3 metres of the fourth lift consist of silty to sandy dolostone and constitute a lower green marker. A shale interbed 15 cm thick occurs 70 cm below the top of the fourth lift. Stylolites and gypsum molds occur in the limestone beds and calcite-filled vugs in dolostone.

The first description of alkali-carbonate reactivity (Swenson, 1957) followed deterioration of concrete used in the construction of Barriefield Barracks. The first lift of the Pittsburg quarry (Table 2) supplied the

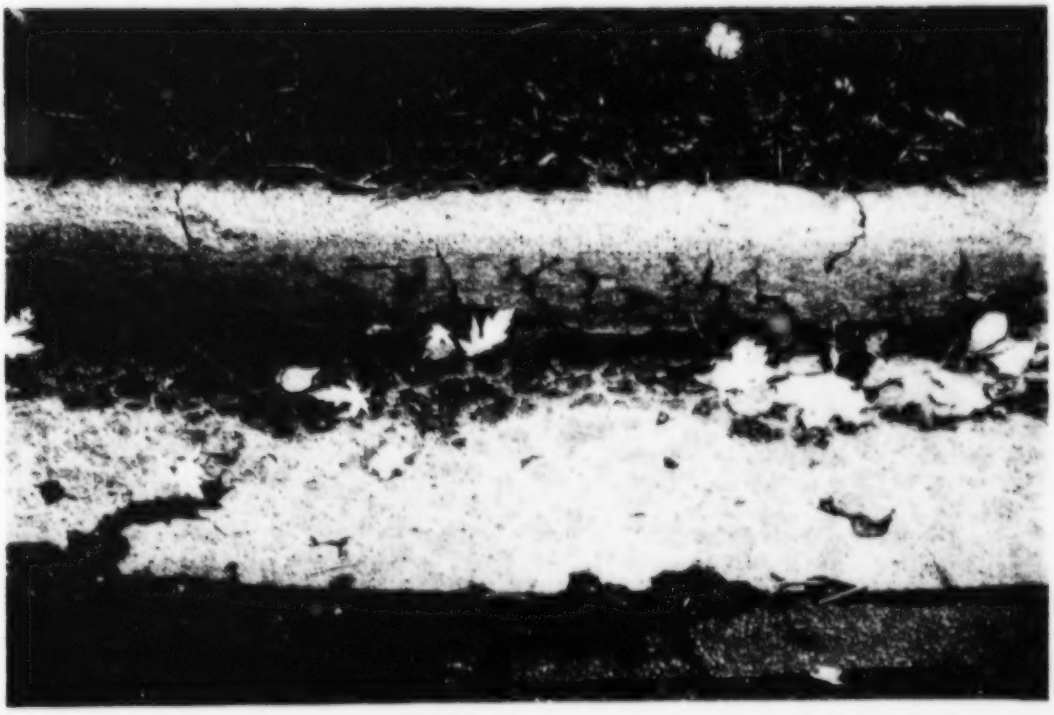

Plate 1. Curb and gutter at Polson Park subdivision in Kingston after 33 years. The cracking and staining here are typical of worst performance within the subdivision. Constructed with Pittsburg quarry stone and low alkali cement.

aggregate responsible for expansion of the concrete. Concrete prism expansion testing and selective quarrying were employed to supply non-reactive rock from other sources for the completion of Highway 401 construction in the Kingston area. Subsequent studies of reactivity of Pittsburg quarry aggregate are as follows: Swenson (1958); Swenson and Legget (1960); Swenson and Gillott (1960); Hadley (1961); Gillott (1963); Smith (1964); Hadley (1964); Swenson and Gillott (1964, 1967); Dolar-Mantuani (1972); Smith (1974); Pagano and Cady (1982); Dolar-Mantuani (1983); Rae (1984); and Rogers (1986). Reactive beds occur throughout the Gull River Formation but a high proportion of them are contained in the lower half of the first lift of the Pittsburg quarry (Figures 13 and 14, Table 3).

The Canadian Standards Association sponsored a multi-laboratory study of the precision of the concrete prism expansion test using coarse aggregate from the first lift of the Pittsburg quarry (Rogers, 1990) (Figure 15). The multi-laboratory variation was the same for all storage conditions and the average coefficient of variation was 23.4%.

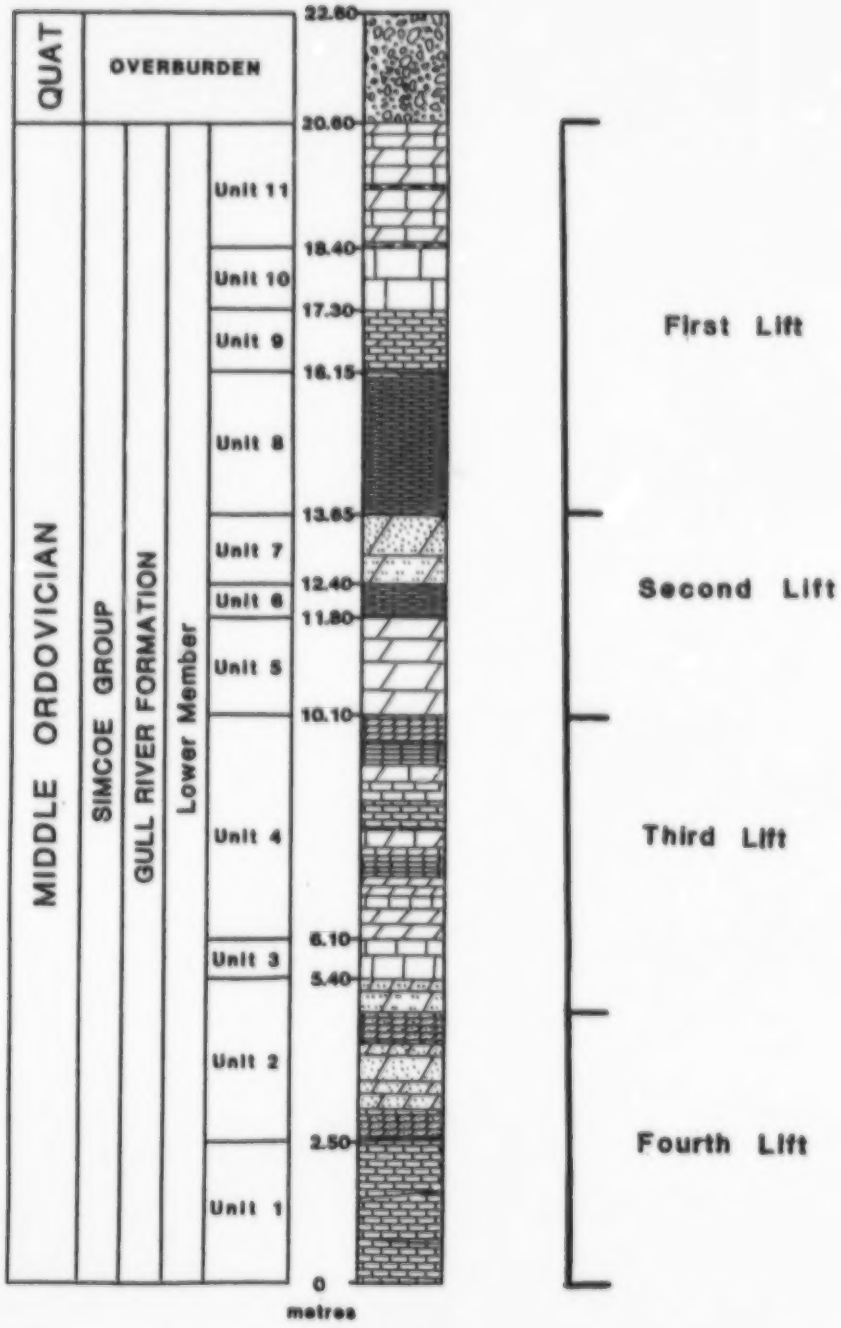

Figure 12. Stratigraphic column for the Pittsburg quarry (from Derry Michener Booth and Wahl and Ontario Geological Survey, 1989, Figure NP-32-2, by R. R. Wolf).

LABORATORY TEST	SAMPLE DATA
Petrographic Number Concrete	127
Absorption, per cent	0.72
Bulk Relative Density	2.712
Magnesium Sulphate Soundness, loss in per cent	4
Los Angeles Abrasion, loss in per cent	18.7
Material Wash Pass 75 µm sieve, per cent	1.55
Heat Loss @ 900°C, per cent	39.7
Insoluble Residue, per cent	10.4
CaO, per cent	40.8
MgO, per cent	6.7
SiO_2 & Al_2O_3	2.4
Petrographic Composition:	
Good Dolomitic Limestone	91.9
Slightly Shaley Dolomitic Limestone	5.5
Shaley Dolomitic Limestone	2.1
Shale	0.5

Table 2. Physical properties of aggregate from the first lift of the Pittsburg quarry.

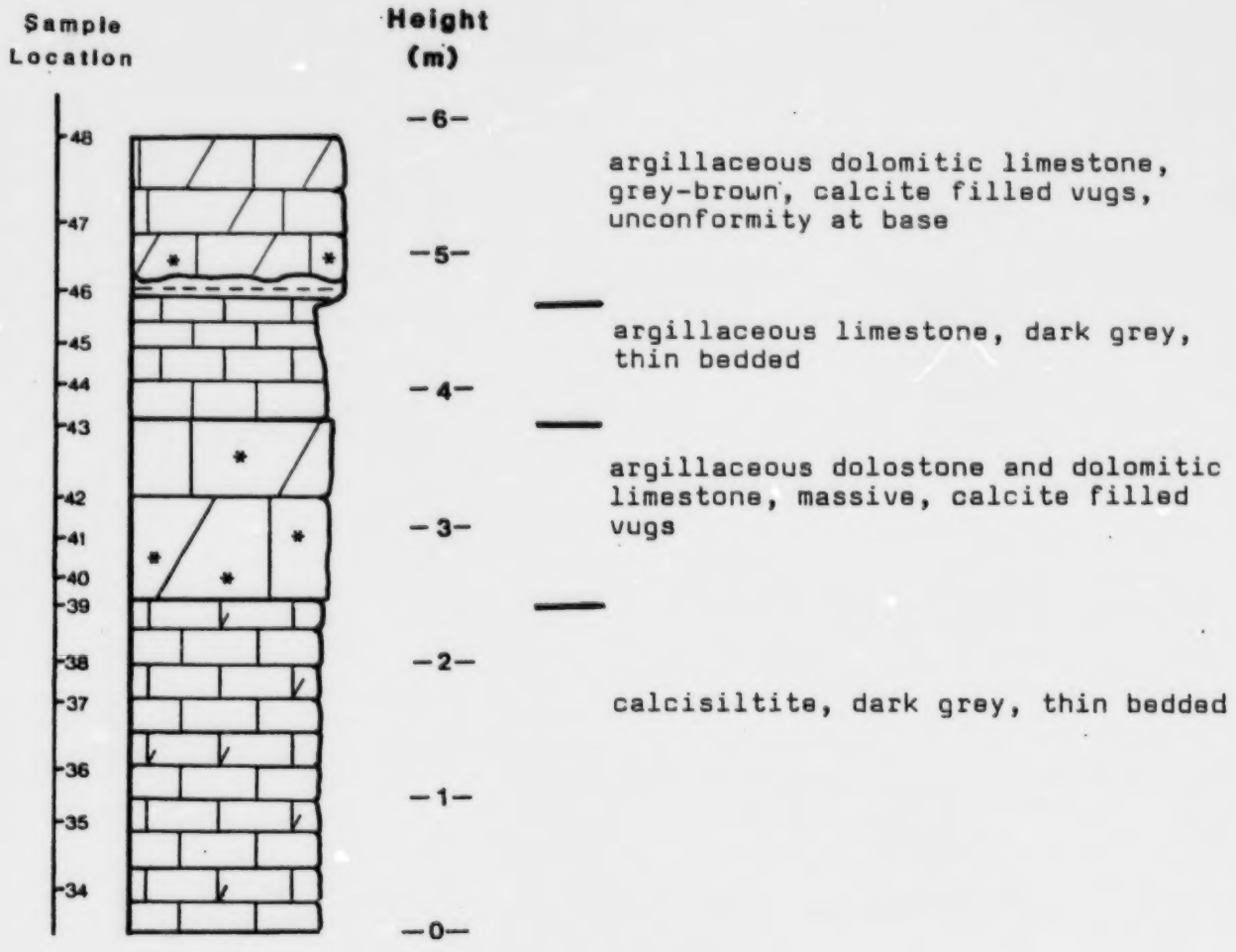

Figure 13. Stratigraphic column for the first lift of the Pittsburg quarry showing sample locations (from Rae, 1984).

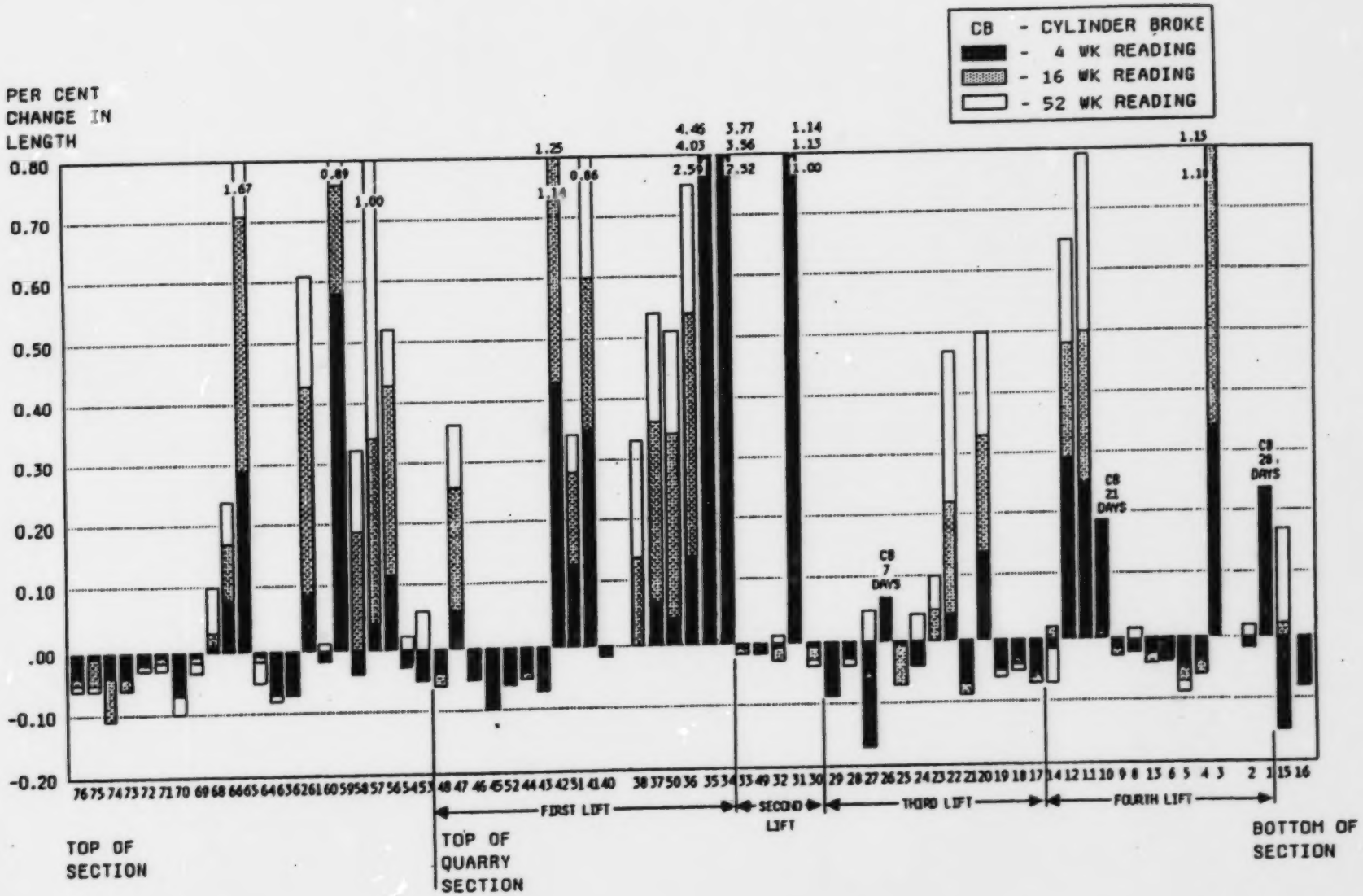

Figure 14. Expansion of rock cylinders (ASTM C-586) for the Pittsburg quarry and Montreal Street rock cut.

SAMPLE NUMBER	CHEMICAL ANALYSIS									ROCK CYLINDER EXPANSION, PER CENT				
	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	CO_2	L.O.I.	CaO:MgO	Insol. Res. %	4 wks.	12 wks.	16 wks.	24 wks.	52 wks.
P.34	10.0	2.86	0.61	4.97	37.2	39.8	37.8	7.5	13	2.52	3.36	3.56	3.72	3.77
P.35	10.8	3.00	0.82	4.49	36.4	38.6	37.3	8.1	16	2.59	3.74	4.03	4.27	4.46
P.36	12.2	3.55	0.71	3.21	35.9	37.5	36.5	11	18	0.14	0.44	0.54	0.70	0.75
P.37	4.95	1.31	0.30	1.72	48.6	43.0	41.1	28	6.7	0.07	0.29	0.36	0.49	0.54
P.38	6.10	1.68	0.39	1.76	46.6	41.7	40.2	27	8.2	0.00	0.01	0.14	0.25	0.33
P.39	9.91	3.01	0.69	2.74	38.8	39.0	37.5	14	15	-	-	-	-	-
P.40	11.5	3.56	1.49	14.6	26.7	39.8	38.7	1.8	16	-0.02	-0.01	-0.01	0.00	-0.01
P.41	7.03	2.00	0.58	8.51	37.0	43.4	41.5	4.4	8.2	0.35	0.51	0.60	0.77	0.86
P.42	12.6	3.83	0.72	4.28	34.7	38.1	36.9	8.1	17	0.43	1.01	1.14	1.22	1.25
P.43	6.59	2.02	0.81	14.7	31.2	44.4	41.7	2.1	7.8	-0.07	-0.08	-0.06	-0.07	-0.07
P.44	2.12	0.29	0.32	1.45	52.1	42.5	42.1	36	3.2	-0.04	-0.05	-0.05	-0.05	-0.05
P.45	1.85	0.27	0.28	1.97	51.8	44.9	42.7	26	2.5	-0.10	-0.09	-0.09	-0.09	-0.08
P.45D	1.85	0.28	0.28	2.01	51.9	44.6	42.6	26	2.4	-	-	-	-	-
P.46	2.97	0.63	0.31	2.33	50.9	44.7	42.5	22	3.6	-0.05	-0.03	-0.03	-0.03	-0.02
P.47	2.98	0.96	0.39	8.02	42.2	45.2	43.2	5.3	3.7	0.06	0.22	0.26	0.32	0.36
P.48	5.26	1.22	0.90	16.6	31.6	46.3	43.4	1.9	5.1	-0.04	-0.05	-0.06	-0.04	-0.02

Table 3. Chemical analyses and rock cylinder expansion test results of samples from the first lift of the Pittsburg quarry (see Figures 7 and 8).

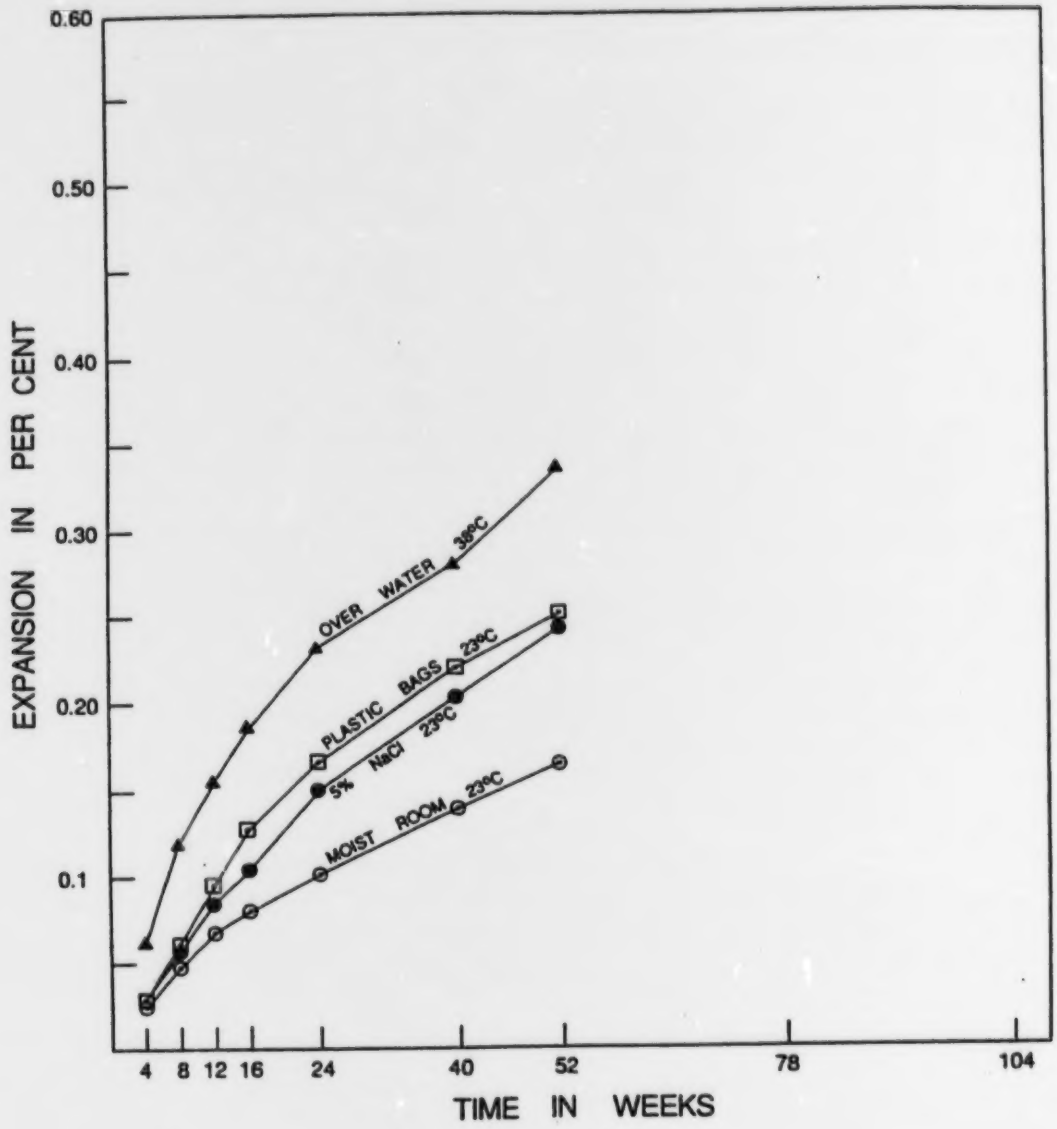

Figure 15. Average expansion of concrete prisms (CSA A23.2-14A) for various storage conditions in multi-laboratory study using coarse aggregate from the first lift of the Pittsburg quarry (from Rogers, 1990, Figure 3).

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